Radiation Protection Issues of the Top-Up Operation of BESSY[1]

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Abstract

BESSY is in operation since 1998, it was designed for decay - mode user operation . The acceleration of the electrons occurs with a 50 MeV preinjector and a full energy synchrotron (1.9 GeV). At 22nd October 2012 BESSY got the operating licence for the top-up operation. This was the final result of years of R&D work of the BESSY accelerator people [1] to improve the injection efficiency, the improvement of insertion devices to reduce field errors and the commissioning of the linac, which replaced the microtron as preinjector and the planning work to accomplish the radiation safety [2].
We focus here on the aspects of radiation safety and discuss the two fundamental questions: Are the shielding walls sufficient, because the shielding was not designed for the top–up mode? (The top-up mode is conducted at high current, the life time is shorter, more electrons must be injected).
Are the safety measures sufficient to hold the annual dose limit also in the areas close to the front-ends? (The top-up injection occurs at opened beamshutters).
We used FLUKA[3],[4] to calculate the doses through the opened beamshutters for different loss scenarios and discuss the resulting safety measures. We present the way how top-up is controlled and why we use the injection efficiency for this task instead of values from active radiation monitors [5].
Finally we present our experiences of the first months with the top-up mode.

1. Introduction

The light source BESSYII supplies 52 beamlines with synchrotron radiation. The storage ring has a circumference of 240 m divided into 16 sections. Two straight sections are used for septum and cavities, four straights host super conducting insertion devices, two 7 T multipole wigglers and two wave length shifters.
The rest of the straights are filled with planar and apple type undulators, wigglers and a pair of undulators used in the femto slicing section. Also several dipole beamlines are in usage.
The beamlines of the super conducting insertion devices are positioned in hutches. The critical energy of the synchrotron spectra of the normal conducting insertion devices and the dipoles are below 2.5 keV. So the 2 mm stainless steel of the vacuum system is sufficient to absorb the synchrotron radiation at those beamlines. Thinner materials like bellows are shielded by a lead sheet, lead glass is used for windows.
The user operation started in 1998, first with the maximum current of 200 mA, then from 2001 on wards with 300 mA.
Since 2003 the experimental hall is accessible for non-radiation workers. Exceptions are areas close to the front ends. Within these areas the 1 mSv limit cannot be held due to bremsstrahlung and the effects of stochastic beam dumps which have been calculated by Fluka to determine the boundaries of these areas [6].These areas include the locations of mirror chambers, that separate synchrotron radiation from bremsstrahlung and the absorbers of the bremsstrahlung. The mirror chambers are remote controllable to adjust the position of synchrotron radiation at the experiments.
In 2008 a two week top-up test has been successfully accomplished [1]. But only one planar undulator and a super conducting insertion device has been used during this test. During the two week test 90 % injection efficiency has been reached. But to hold this value also with all other insertion devices, the injection has to be improved further.
2010 the microtron has been replaced by a 50 MeV linac. The reason was the intended single bunch injection for the top-up operation which requires a device that can accelerate considerable higher single bunch charges as it is possible with a microtron. The commissioning of the linac was completed in 2011, but the single

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bunch charge was somewhat below the design values, so the top-up injections are conducted with a four single bunches train with variable injection timing, to produce a multi-bunch filling with a hybrid bunch for time resolved experiments.
In 2012 the improvement of the injection efficiency > 90 % if all insertion devices are in usage has been completed. Based on the safety report [6], which includes the prognosticated doses and dose rates and the detailed description of the interlock system, the authorities gave the operation licence for the top-up mode at 22nd October 2012.

2. Electron losses

Every electron injected in a storage ring gets lost, a part directly during injection. This is expressed by the injection efficiency which is the fraction of the electrons successful stored divided by the injected electrons. The stored electrons get lost later by collisons with the rest gas molecules within the vacuum tube and much more important, because of the low pressure of 1E-12 bar, by collisions with other electrons. The Touschek rate results from the scattering of electrons within the bunch. The two scattered electrons will be lost if their energy gain/loss is outside the dynamic aperture of the ring. The life time is determined by the Touschek rate which is proportional to the electron density in the bunches. It was intended to use the top-up mode at currents close to the maximum storage ring current of our operating licence for the decay mode at 300 mA. Because the life time is shorter at higher currents, the top-up operation requires considerable more injected electrons as the decay-mode, if the top-up operation is conducted at the maximum current of the decay-mode as it is the case at BESSY.
The radiation through the shielding walls is proportional to the total number of electrons lost in the storage ring. So, if more electrons should be injected because of the reduced life time, the injection efficiency has to be increased to reduce the losses during injection to keep the overall number of electrons lost in the storage ring constant. Otherwise the annual dose rises with the number of injected electrons, which is not possible at many storage rings where the 1 mSv/a limit should be kept.
The machine test operation is conducted in the same way as before with closed beamshutters and usually in decay mode, so we consider only the injected electrons during user operation in detail.
We have summarized the electron losses for the two modes in table 1. The injected and successfully stored charge for the top-up mode is 3.2 times higher than it is for the decay – mode. This has to be compensated by increasing the injection efficiency from 30 % to 90 % for the top-up mode to inject about the same number of electrons into the storage ring per year. Otherwise the annual dose through the walls would rise by the same factor. The top-up injection scheme (0.5 mA every 30 sec) corresponds to a life time of 5 h.

	Decay mode	Decay mode	Top-Up mode	Top-Up mode
Operation time	250 days/a	6000 h/a	250 days/a	6000 h/a
Injections	3/day	750/a	2880/day (30 sec)	720000/a
Current added in SR	150mA /injection	112.5 A/a	0.5 mA /injection	360 A/a
Charge		9.0E-5 C/a		2.88E-4 C/a
Efficiency		30%		90%
Electrons	5.62E14e-/a	**1.9E15e-/a**	1.80E15e-/a	**2.0E15e-/a**

Tab.1 –Overview of BESSY annual electron losses

Because the number of injected electrons per year is about the same for the two modes, the doses through the shielding walls will be the same for the top-up mode as it was for the decay mode.

3. Doses and dose rates

Beside the doses through the shielding wall also the doses and dose rates through the opened beamshutters have to be considered carefully. If the storage ring current is below our limit (200 mA) no top-up injection shots are possible. We consider here the case when an error suddenly occurs, e.g. a short in a dipole magnet. Even in such a case it takes several seconds until the dipole is without field. If during that time an injection shot occurs (I > 200 mA), it could be that the new injected shot is lost in the straight or as worst case reaches the experimental hall. If a dipole has a short, electrons can always reach the experimental hall through a 0 degree beamline.

To show that this is possbible also through dipole beamlines we calculated trajectories through BESSY dipoles. They have a deflection angle of 11.25 degrees and are operated with 1.3 T for the electron energy of 1.7 GeV. The sequence at BESSY is straight, dipole 1, dipole 2, straight. From dipole 1 two beamlines are possible at 4 degree and 6.7 degree. From dipole 2 only a 2 degree beamline is possible, but there are only two such beamlines at BESSY. At first we show the trajectory as it should be in fig. 2 (red line) , included in the graph is the 4 degree beamline. In the plots the beamline is drawn up to its source point, in reality the beamlines begins at the vacuum chamber of the dipole.

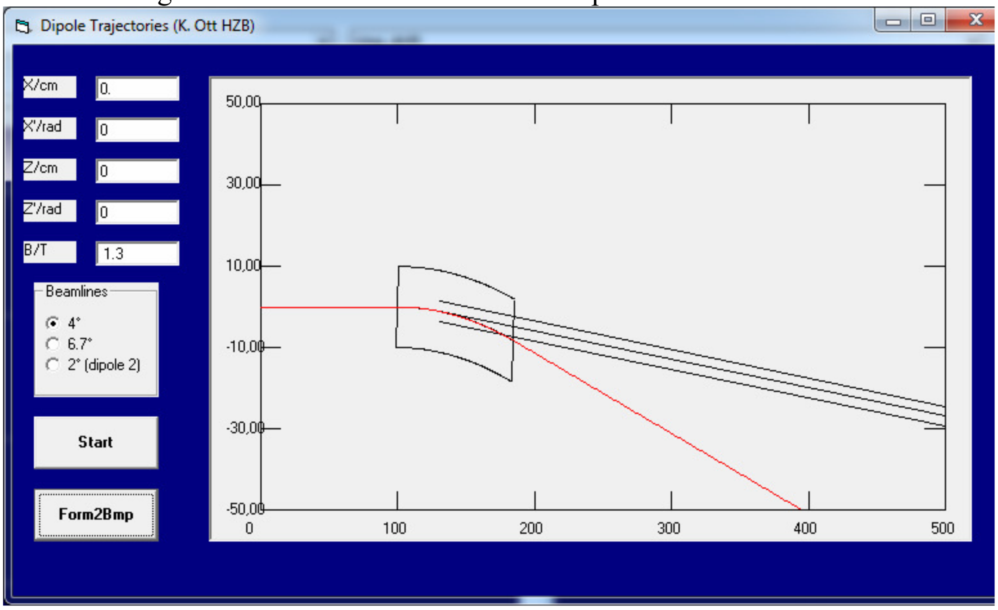

Fig 1: Trajectory through dipole (red line), B=1.3 T, E = 1.7 GeV

Next we calculated a trajectory through a dipole, where the injected beam reaches a dipole beamline using a reduced dipole field and a horizontal offset. The results are shown in fig. 2.

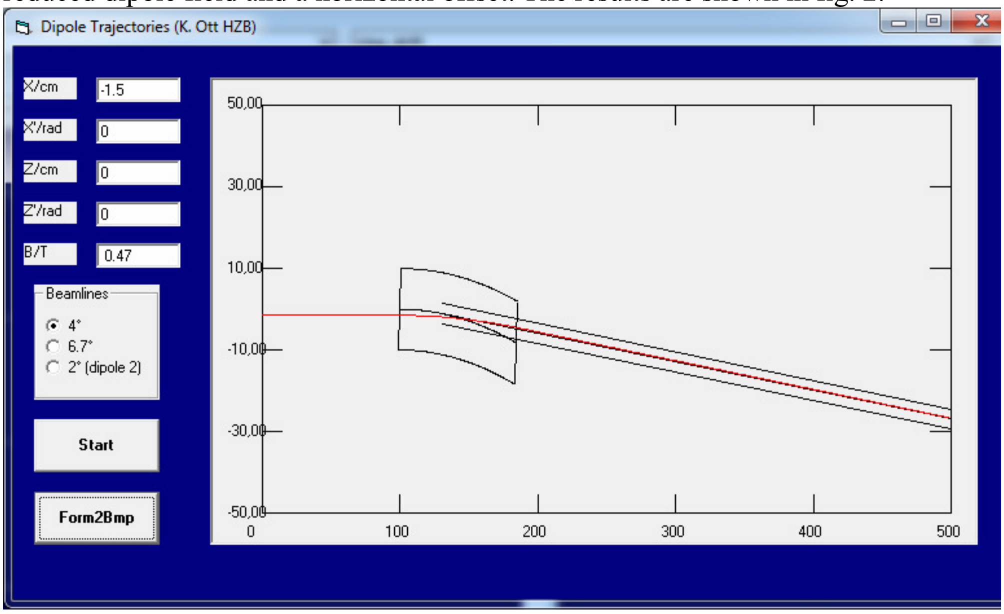

Fig 2: Trajectory through dipole beamline (red line), reduced field B = 0.47 T, horizontal offset -1.5 cm, E = 1.7 GeV

It is clearly shown that even dipole beamlines could be reached by injected electrons. In contrast to the undulator beamlines two error conditions are the prerequisite for such occurences. So the probability is quite small, but because of our safety measures (see below) even such occurences will not lead to dangerous expositions.
Now we will focus on undulator beamlines and consider the cases where one injection shot is lost at the straight section or one shot reaches the experimental hall because of a short in a dipole magnet. We considered three scenarios: 1.) the injected shot reaches the experimental hall through an undulator beamline, 2.) the injected shot is absorbed at a thin iron target of one radiation length in the tunnel (dipole chamber, taper etc), 3.) the injected shot is lost at an undulator chamber (aluminum) at an angle of 1 mrad. The results for the gamma radiation is summarized in fig. 3. In all cases the charge of 1 nC is used. The bremsstrahlung or the electrons hit the mirror chamber, penetrate the silicon block and hit the absorber of the gas bremsstrahlung. The complete area is an interlock saved exclusion area, surrounded by fences. The highest doses are 3.2 μSv/shot if the shot is injected in the experimental hall, or 1.0 μSv/shot if the electrons are lost at the straight section. The difference is only a factor of three, so even if the injection into the experimental hall is blocked by the interlock, the bremsstrahlung by losses in the straight has to be considered carefully. Our solution to this problem is described below.

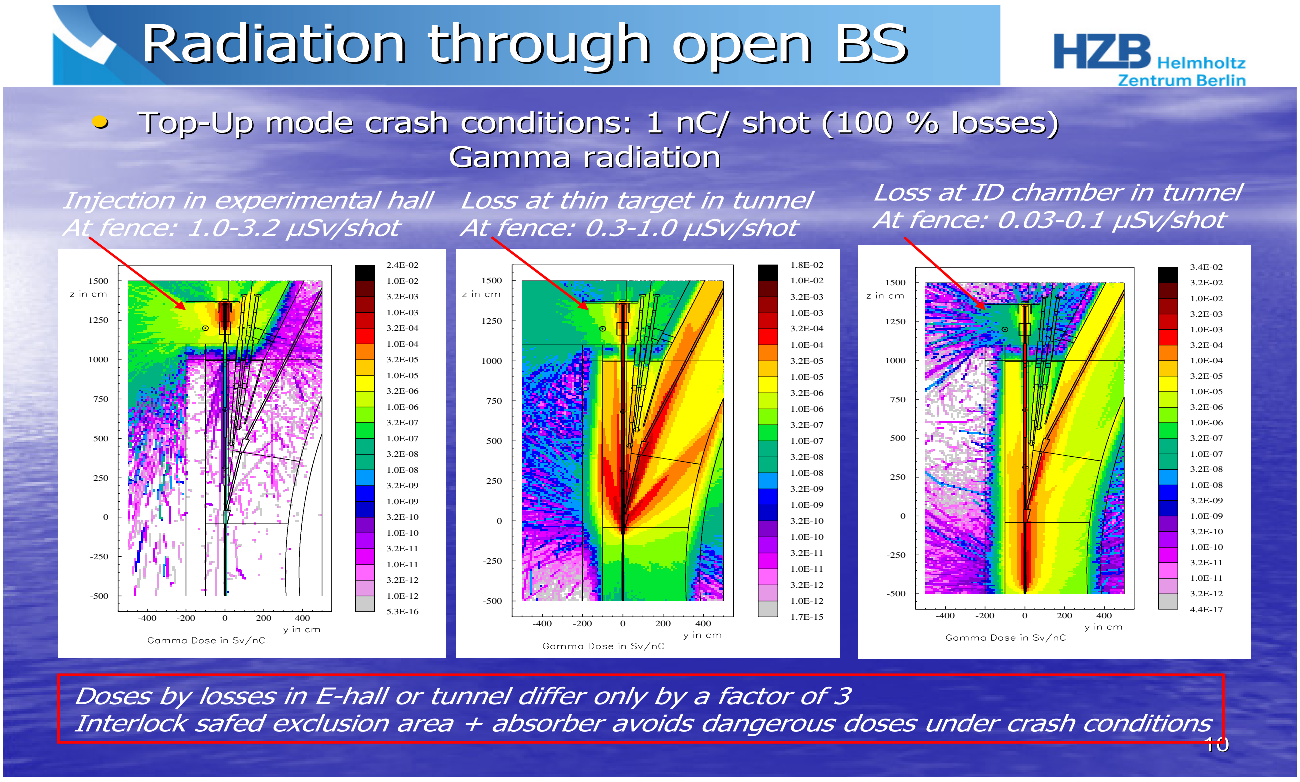

Fig. 3, Gamma doses if a shot of 1 nC is lost in the straight section or injected into the experimental hall.

In figure 4 we show the results of the same scenarios for the neutron radiation. In that case the injected beam leads to a factor of twenty higher neutron doses to the side outside the exclusion areas. The reason is the increased production of neutrons within the bremsstahlung absorber. In forward direction the 30 cm of lead reduces also somewhat the neutron doses, but we increased the shielding in this direction by 20 cm PE, which is a tenth value layer.

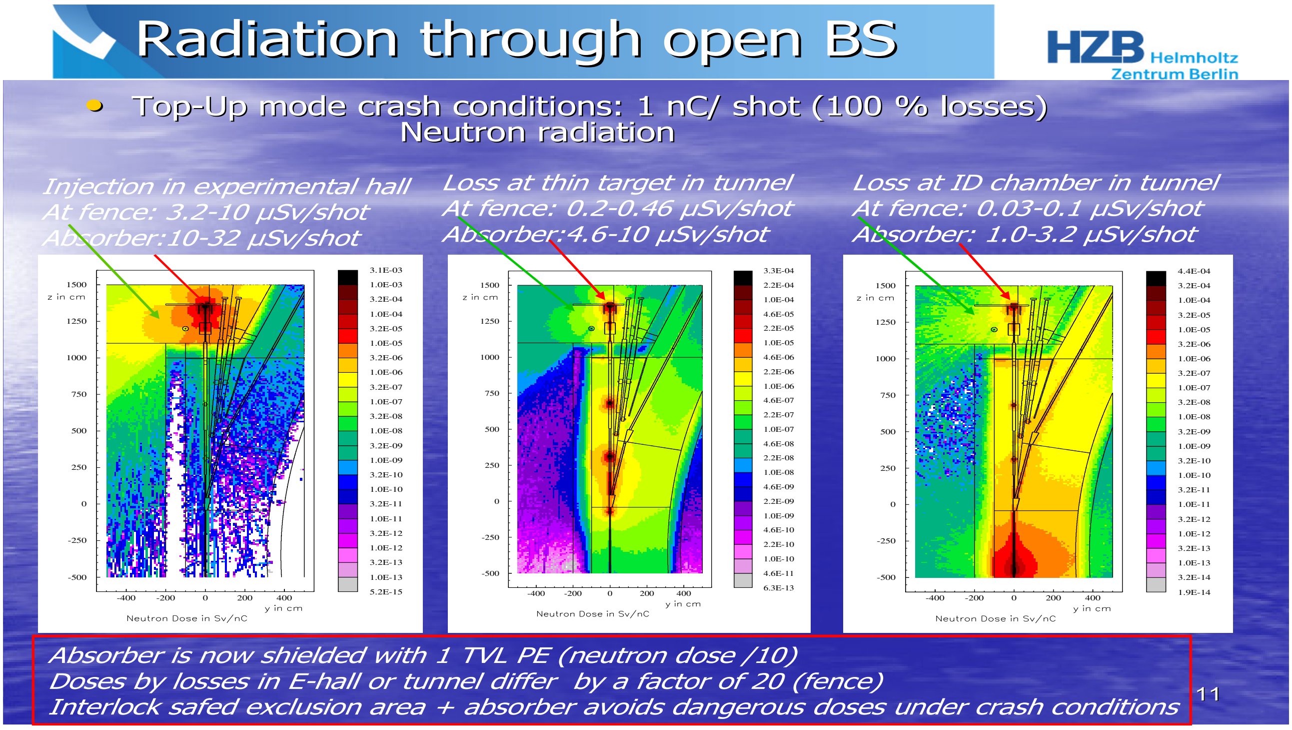

Fig. 4, Neutron doses if a shot of 1 nC is lost in the straight section or injected into the experimental hall.

We used the two scenarios where the electrons are lost in the tunnel completed by a third scenario where the electrons are lost downstream the first dipole to calculate the annual dose around the front ends. The results of this calculations are given in table 2. The calculations uses the 2E15 electrons per year that are injected during the top-up mode. The doses are the highest values at the fence in transversal direction (arrows in fig. 3).

Scenario	Gamma dose (average of range)	Neutron dose (average of range)	Sum
Thin target	6.6 mSv/a	7.3 mSv/a	13.9 mSv/a
Undulator chamber	0.66 mSv/a	1.6 mSv/a	2.26 mSv/a
Downstream dipole	0.066 mSv/a	0.16 mSv/a	0.226 mSv/a

Tab. 2, Annual doses at the fence

The average of the three scenarios results in an annual dose of 5.46 mSv/a for 6000 h/a or 1.82 mSv/a for 2000 h/a. During the test operation the experimental hall is therefore radiologically controlled area and the users and employees working there are considered as radiation workers category B who are allowed to get up to 6 mSv/a during work. If the 1 mSv limit can be hold also around the front-ends in the accessible part of the experimental hall has to be verified by measurements during the test operating phase which lasts one year.

4. Safety measures

The safety measures are intended to reach the dose limit of 1 mSv/a in the accessible part of the experimental hall. In Germany also the dose rate limit of 3 mSv/h has to be held under any circumstances in areas that are not interlock safed exclusion areas. The dose rate limit requires to consider any possible crash condition carefully, for the top-up operation radiation fields through the opened beamshutters are especially important. Because of the measurement errors of radiation monitors due to pulsed radiation and the high energy part of the neutron specctrum we decided to use the injection efficiency to control the top-up operation. The measurement of the injection effciency is based on the measurement of the synchrotron current and the increase of the storage ring current after the injection shot. The measurement of these values is much more accurate and much faster as it is the case for the measurement of doses. The injection efficiency is given by:

$$\eta = \frac{2.5 \cdot \Delta I_{SR}}{I_{SY}} \cdot 100\% \qquad (1)$$

The factor 2.5 is the quotient of the circumferences of storage ring (240 m) and synchrotron (96 m). The currents in the storage ring and the synchrotron are measured by DCCTs. There are two such devices in the synchrotron and the storage ring respectively. The calculation of the injection efficiency is conducted by two independent real time systems. The injection efficiency is used for several safety measures which are described below.

4.1 Linac and synchrotron

The synchrotron has a convolution time of 320 nsec. The former microtron was therefore operated with a pulse width of 200 nsec, because multiturn injections are not possible. The maximum pulse current of the microtron is 10 mA, so we have a maximum charge of 2 nC/shot. At Linacs the maximum accelerating voltage is proportional to the square root of the rf power coupled into the accelerating structure by the clystron.

$$U = K \cdot \sqrt{P_{rf} \cdot l \cdot r_0} \qquad (2)$$

U is the accelerating voltage, the proportional factor K is about 0.8, P_{rf} is the rf power during the pulse, l is the length of the accelerating structure, r_0 is the shunt impedance which is for example 53 MΩ for the SLAC structure. To reach 50 MV accelerating voltage several MW of the pulsed rf power are necessary. Therefore, the power is available to accelerate charges two orders of magnitude higher than the mictroton limit. So our first safety measure is a charge limit for the linac that is included in the linac PLC and defines maximum pulse lengths and pulse heights. This measure limits the charge to 2 nC/shot and therefore the maximum dose rates cannot be higher as they were during the former microtron operation. The maximum charge for a single bunch is 0.6 nC/shot. This value is much higher than the maximum single bunch value of the microtron but below our overall charge limit.

The measurement of the synchrotron current is used for the calculation of the injection efficiency and because of the fast acceleration process in the synchrotron (accelerating time from 50 MeV to max. 1.9 GeV is about 50 msec) the measurement error of this value is higher than the current measurement in the storage ring. To improve the situation we defined a minimum of 0.3 mA (or 0.1 nC) of the synchrotron current to keep the measurement error of this value below 1 %. If the synchrotron current value is lower, no extraction occurs, the electrons are decelerated and lost at energies about 50 MeV.

During the decay mode injections linac and synchrotron are operated with 10 Hz. Because of the White circuits this operation frequency of the synchrotron magnets has to be kept for the top-up operation. But the linac frequency is reduced to 1 Hz and the extraction out of the synchrotron is reduced to 0.1 Hz. (The reduction of the linac operation to 0.1 Hz as well led to stability problems in the linac.)

The reduction of the maximum extraction frequency reduces the maximum possible dose rate by a factor of 100. This is especially important because of the opened beamshutter during injections.

The pulsed elements (extraction kicker, extraction septum, storage ring kicker, injection septum) are all operated with 0.1 Hz during top-up operation. This is generated using a frequency divider circuit switched and controlled by the top-up interlock. The reduced frequency makes the operation of the pulsed elements more stable and is one of the reasons that the high injection efficiency > 90 % could be reached.

4.2 Storage ring

If the storage ring current is below the defined limit an application program enables the injection into the storage ring at maximum 0.1 Hz until the storage ring current is higher than this limit.
Injection shots into the experimental hall are only possible at severe error conditions that make a stored beam impossible, for example a short in a dipole magnet. The top-up interlock blocks extractions out of the synchrotron if the stored beam in the storage ring is < 200 mA.
If a short in a dipole occurs it lasts several seconds until the beam is dumped. In such a situation it could be possible, that an injection shot still passes the interlock conditions and is lost in the straight section or even reaches the experimental hall. For these situations we defined an injection efficiency that immediately stops the top-up operation to prevent the injection of the next shot. If the injection efficiency is < 60 % the top-op operation is stopped by blocking the extraction and the linac operation. In that case the next injection has to be done under decay – mode conditions with closed beamshutters until at least 60 % are reached again before top-up injections are unblocked.
The 90 % efficiency limit must be held over an 4 h average. If the efficiency is < 90 % in the next block (or blocks) no injection is possible during a penalty time. This penalty time is defined by:

$$\Delta T = 4h \cdot \frac{90\% - \eta}{100\% - 90\%} \tag{3}$$

The injection efficiency during the penalty time is calculated with 100 % because no injection is possible.
The procedure is similar to other synchrotron light sources that control top-up operation with radiation monitors and defined a 4 h dose (2 μSv) for that reason.
As we have shown above, the number of injected electrons / year is the same as for the decay mode if the injection shots occur every 30 sec. This corresponds to a life time of 5 h. Because injection shots are possible every 10 seconds we included also the life time as condition for the top-up interlock. The life time is also measured shot by shot. If the life-time is < 5 h the extraction out of the synchrotron is blocked.

4.3 Experimental hall

The safety measures that we have installed in the past around the front ends in the experimental hall to protect the users from stochastic beam dumps, bremsstrahlung and scattered bremsstrahlung are also useful for the top-up operation. At every section there are interlock safed exclusion areas. The opening of doors of these areas is only possible if there is no injection operation and if all beamshutters of the given section are closed. Inside these areas (which could also be a hutch at sections with superconducting insertion devices) the mirror chambers are located, that separate synchrotron radiation from gas bremsstrahlung. The synchroton radiation is deflected, the bremsstrahlung penetrates the mirror (silicon block) and is absorbed in the downstream bremsstrahlung absorber out of 30 cm of lead. Behind the lead absorber are 20 cm PE to absorb neutrons produced by the bremsstrahlung. Scattered bremsstrahlung is absorbed by a lead wall (about 1 m²) with 10 cm thickness in forward direction. Also, in case of dipole beamlines the mirror chamber and subsequent bremsstrahlung absorber is located in these areas. The transversal distance to the fence (or hutch wall) is large enough, so that scattered gas bremsstrahlung to the side is not measurable there. There is one exception, where inside a hutch a transversal lead shielding is necessary. In that case the reason is not the gas target in the straight, but two tapers with small aperture close to our 7 T multipole wiggler, that causes higher bremsstrahlung by electron losses that reduces the life time.
As we have shown by Fluka calculations, even if one injection shot reaches the experimental hall, the bremsstrahlung absorber reduces the resulting dose to an non-dangerous level outside the exclusion areas.
The injection efficiency is measured shot by shot worth two redundant systems. At such an occurance the injection efficiency is < 60 % which causes an immediate stop of the top-up operation. To start the top-operation again, one has to inject with closed beamshutters until the efficiency is > 60 % first. If this condition is fulfilled, the top-up mode can be switched on again.

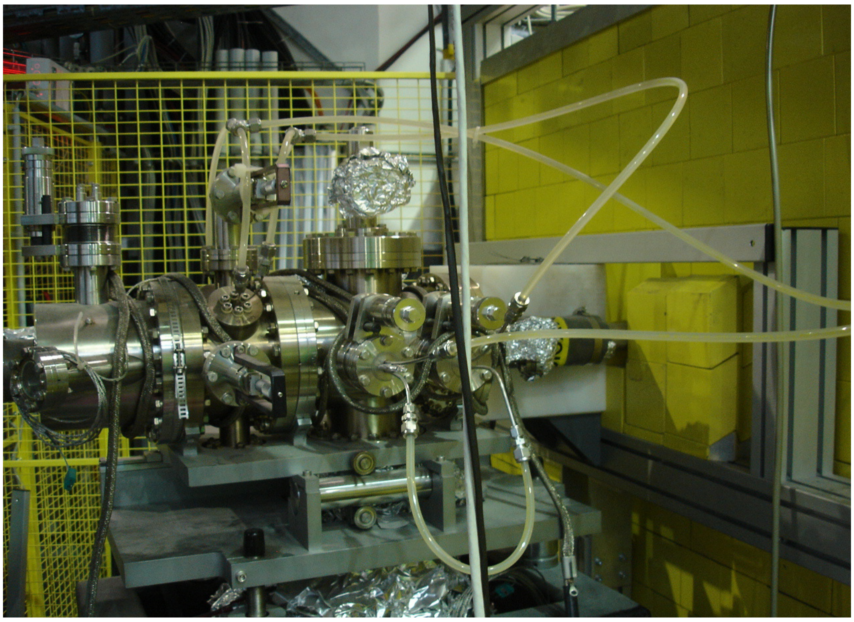

Fig. 5, Bremsstrahlung absorber in the experimental hall with subsequent PE absorber (20 cm), the lead absorber has a overall thickness 10 cm and of 30 cm in the center

5. Measurements

At BESSY we have a measurement system of 40 stations consisting of a BF_3 neutron monitor and a ionisation chamber each. In the experimental hall 16 of these stations are located outside the storage ring wall at the closest transversal distance to the machine. The shielding wall at BESSY consists of 1 m ordinary concrete to the side in the direction of the experimental hall, 1 m of haematite concrete at the ratchet end walls with an additional lead stripe of 5 cm thickness (10 cm at the injection region). Because the decay mode injections occurs with 10 Hz, dose rates of several hundred µSv/h neutron dose rate are possible if the injected beam is completely lost at the position of a station (transversal scenario). We therefore investigated the measurement errors of our neutron monitors due to the dead-time effects of pulsed radiation in detail [5]. The true dose rate as function of the measured dose rate is given in figure 6 for three neutron monitors.

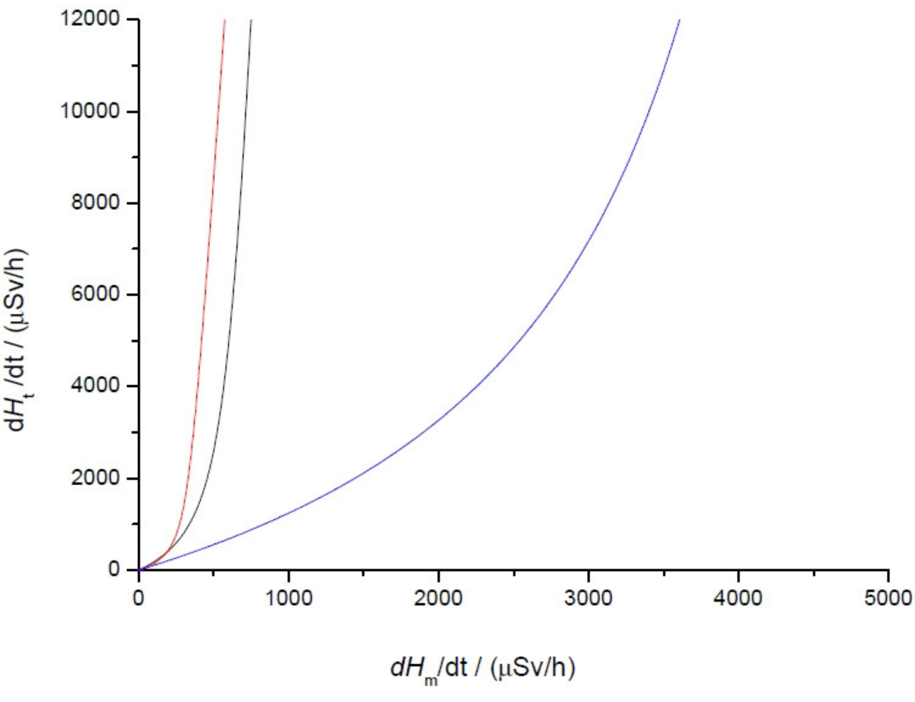

Fig. 6, true dose rates (10 Hz operation) of Biorem A (red) and Biorem B (blue) and LB6419 (black) calculated from measured neutron dose rates H*(10) in µSv/h, Biorem A has a dead-time of 10 µsec, Biorem B 1.9 µsec but are otherwise identical

The correction curves presented in fig. 6 have been calculated from measurements conducted at 10 Hz at MLS [6]. The Biorem A has a slower preamplifier as Biorem B but is otherwise identical. If the Biorem A (10 µsec dead-time) measures 500 µSv/h or 13.9 nSv/shot, the true dose rate is about 10 mSv/h or 278 nSv/shot. The Biorem B (1.9 µsec dead-time) has a much better dead-time behavior, which results from its faster preamplifier. If the Biorem B measures 3.5 mSv/h or 97 nSv/shot the true dose rate is 10 mSv/h or 278 nSv/shot. We therefore replaced our old preamplifiers by the faster ones thereby transforming Biorem A to Biorem B.
The LB6419 had not enough statistics for its included activation monitor, the values are from its ^{3}He counter only.
Beside the errors due to dead-time effects also the errors due to high energy neutrons (E>10 MeV) are relevant. We derived correction factors from calculated neutron spectra at BESSY [7].
Neutron radiation through the walls can be measured now by our neutron monitors with only small dead-time corrections. For the control of the top-up injections this is still not enough, because under crash conditions the neutron dose /shot can be in the µSv range as can be seen in figure 3. (The position at the left corner of the exclusion area for which the Fluka values are given corresponds to the position of the neutron monitors. The distance to the bremsstrahlung absorber is about the same). To measure also high intense pulses we use TLDs in a plexiglass moderator and albedo-dosimeters mounted on the surface of our Biorems (see fig. 7).

Fig. 7, TLDs in plexiglass moderator at the left corrner of the exclusion area, albedo-dosimeter mounted on the surface of Biorem (background)

The disadvantage of the TLDs is that they are not sensitive to measured doses below 50 - 100 µSv. We change the TLDs in three months periods and send them to the state authory to get the results. Up to now we did not measure doses above the natural background with them.

6. Experiences

Up to now the top-up injections could be conducted stable above 90 % for even several days without any limitations in the usage of the insertion devices. Interruptions by the interlock occured mostly because of the 60 % limit for single shots, but these occurences are rare. Interlock failures did not occure, the system works reliably and accurately. The usage of the injection efficiency to control the top-up mode did not lead to any problems so far.
Radiation measured by our active system is not higher as it was during the decay mode. The passive ambient dosimetry did not result in doses above the natural background. This leads to the conclusion that no severe crash operation occured. The personal dosimetry gives the same results as before, only 0.1 % of the dosimeters are above the natural background, and even in these cases the monthly dose caused by the

accelerator is 0.1 mSv. The personal dosimetry is conducted with albedo-dosimeters, they are exchanged monthly. Up to now the change to top-up mode has been successful, the radiation safety is as good as before.

7. Summary

Top-up is a major change for a synchrotron light source designed for the decay-mode. The shielding is designed for a given number of injected electrons per year. The annual doses behind the shielding walls are proportional to this number. Therefore the top-up mode cannot be used to compensate reduced life times by permanent injections.

The top-up operation has advantages for the users though, so we found a way to use the top-up mode but keeping the number of injected electrons the same as for the decay - mode. At BESSY the injection effiency could be rised from 30 % to 90 % with no limitations in the usage of insertion devices.

We use the injection efficiency to control the top-up mode. This is much more accurate and faster than it is possible with radiation monitors. The 90 % injection efficiency must be held in a 4 h average. If not it is compensated by the interruption of the top-up mode for a penalty time during the next 4 h block (or blocks). The injection efficiency is measured shot by shot. If the injection efficiency is below 60 % for a single shot the top-up injections are stopped immediately using two redundant systems. Interlock safed exclusion areas and bremsstrahlung absorbers avoid doses > 10 μSv in the accesssible parts of the experimental hall even if one shot is injected into the experimental hall. The preamplifiers of our neutron monitors have been exchanged by faster ones to reduce dead-time errors. Radiation through the wall is now measurable with very small errors due to the dead-time. Measurement errors due to high energy neutrons (E > 10 MeV), had been corrected by correction factors from calculated neutron spectra. These factors are between 2 and 3 and depend on the material (lower for haematite, higher for ordinary concrete) and the thickness (higher for thicker walls). To be able to measure also more intensive pulsed doses through the front ends as it could be at crash conditons, we use TLDs and albedo - dosimeters for addtional ambient dosimetry. The radiation through the front ends has the same neutron spectrum like inside the tunnel, the maximum is at 1 MeV. In that case no high energy correction is necessary.

The transformation to the top-up mode has been successful, injection effiencies > 90 % can be held even over a several days period. Active ambient dosimetry and personal dosimetry show no increase in comparison with the decay-mode. Passive ambient dosimetry conducted at the exclusion areas show no values above the natural background. The interlock system works reliably and up to now without errors.

8. References

[1] P. Kuske et al., “Preparations of BESSY for Top-Up Operation”, EPAC08, Genoa, Italy, WEPC037 (2008) http://accelconf.web.cern.ch/AccelConf/epac2008

[2] K. Ott , “Aspects of Radiation Safety for a Topping-Up Operation of BESSY”, Rad. Meas. 41 (2007)

[3] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso, J. Ranft, "The FLUKA code: Description and benchmarking", Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6-8 September 2006, M. Albrow, R.. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)

[4] A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, "FLUKA: a multi-particle transport code" CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[5] K. Ott, M. Helmecke, M. Luszik-Bhadra, M. Martin, A. Weber, “Dead Time Effects of Neutron Detectors due to Pulsed Radiation”, Rad. Prot. Dosi. Doi:10.1093/rpd/ncs326 (2012)

[6] K. Ott, “Sicherheitsbericht für den Top-Up Probebetrieb der Speicherringanlage BESSYII in Berlin – Adlershof”, BESSYII int. report (2012)

[7] K. Ott, “FLUKA Calculations of Neutron Spectra at BESSY“, EPAC06, Edinburgh, UK, THPLS018 (2006) http://accelconf.web.cern.ch/AccelConf/epac2006